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HIGH PRESSURE ELECTRONIC TRANSPORT IN SEMICONDUCTORS
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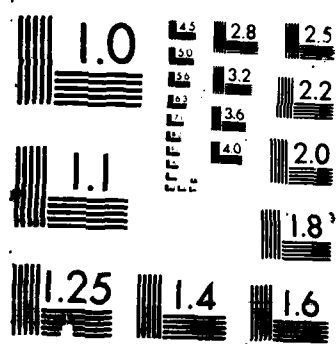
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HIGH PRESSURE ELECTRONIC TRANSPORT
IN SEMICONDUCTORS

Final Report

Ian L. Spain
James R. Sites

September 1987

U.S. Army Research Office

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Colorado State University
Fort Collins, Colorado 80523

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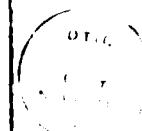
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19 ABSTRACT (Continue on reverse if necessary and identify by block number) Research has resulted in (1) developing galvanomagnetic measurements in the diamond anvil and/or sapphire anvil cells to pressure of about 10 GPa, (2) Performing electrical resistivity, magnetoresistance, Hall effect, and Shubnikov-de Haas measurements on bulk samples of GaAs and InP, and (3) Carrying out I-V and C-V measurements on Schottky diodes of GaAs and InP and MIS Structures.				
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HIGH PRESSURE ELECTRONIC TRANSPORT

IN SEMICONDUCTORS

1. STATEMENT OF GOALS

- (1) To develop techniques for carrying out electrical and galvanomagnetic measurements in the diamond anvil and/or sapphire anvil cells to pressures of about 10 GPa.
- (2) To carry out electrical resistivity, magnetoresistance, Hall effect, and Shubnikov-de Haas measurements on bulk samples of GaAs and InP.
- (3) To carry out I-V and C-V measurements on Schottky diodes of GaAs and InP and MIS structures.
- (4) Time permitting, to extend the measurements to transferred-electron effects and quantum effects in inversion channels at low temperature.

Progress was made in 1-3, but not 4. However, two other phenomena were investigated:

- (5) Photoluminescence studies of bulk InP and GaAs/AlGaAs multiple quantum wells.
- (6) X-ray diffraction studies to determine the equation of state and high pressure phases of InP, and to study metastable phases that were discovered for Si, GaAs, InP, and related alloys.

Progress in each of these areas will be discussed briefly, with details appearing in journal articles listed in Section 3.

2. SUMMARY OF RESULTS

2.1 Experimental Techniques

The major accomplishment in this area was the development of techniques for carrying out electrical and galvanomagnetic measurements in the diamond anvil cell (DAC) (Patel, Crumbaker, Sites and Spain, 1986). Such measurement required the development of techniques for preparing samples of the order of $100 \times 100 \times 30 \mu\text{m}$, and attaching leads to them (Patel and Spain, 1987). As far as we are aware, we are the only group in the world that has carried out galvanomagnetic measurements in the DAC.

The above capability also allowed capacitance and conductance measurements to be carried out on Si/SiO₂/Al MOS structures (T. E. Crumbaker, M.S. Thesis, 1987, and to be published). This is the first measurement of this kind, to our knowledge.

The ability to make measurements in the DAC at low temperature and in high magnetic fields depends on the dimensions of the cells. New DACs were constructed which have a cylindrical shape, with diameters as low as 19 mm, and lengths of 45 mm. Construction materials are compatible with operation at low temperature and high fields. A journal article on the construction of miniature cells is in preparation (Dunstan and Spain, 1987).

Apparatus improvements were made in a number of areas, including the fluorescence spectrometer for pressure measurement, photoluminescence measurements at low temperature, and the use of the Hewlett-Packard 9920 computer and ADC for collecting and analyzing data.

2.2 Transport Measurements on GaAs

Resistivity, Hall and magnetoresistance measurements were carried out on several samples of n-type GaAs, both bulk material and epitaxial

layers. The data were analyzed using a simple two-band model to give the band-crossover (Γ to X) pressure of 4.1 ± 0.1 GPa, in excellent agreement with the value obtained from photoluminescence techniques. No evidence of massive carrier trap-out was found, in comparison with other high-pressure results using solid pressure-transmitting media. This possibly indicates that these other methods compress the sample in a non-hydrostatic manner, introducing defects which act as traps. Our research is reported in Patel, Sites and Spain, 1987a.

2.3 Transport Measurements on InP and AlGaAs Alloys

Similar transport measurements were carried out on InP and AlGaAs alloys. It was found that data could be obtained satisfactorily to about 5 GPa, and that problems with the electrical contacts occurred above this pressure. Data are required to about 8 GPa in InP in order to achieve the Γ -X crossover, so that this phenomenon could not be observed. However, the data to 4 GPa were interpreted in terms of models of the scattering processes, reported in Patel, Sites and Spain, 1987b. It is not known at the present time why the contacts develop high resistance above 5 GPa. This problem has to be solved before higher pressure measurements, which are possible in principle, can be made.

2.4 Interface States in Si/SiO₂/Metal MOS Capacitors

We intended to study I-V and C-V characteristics of MOS capacitors fabricated from GaAs and InP, but it proved difficult to prepare them in the form needed for studies in the DAC. Therefore, our study concentrated on Si/SiO₂/Metal capacitors. The lowest conduction band states in Si are X-states, so that only a weak dependence of band-gap on pressure is observed ($dE_g/dP = -50$ meV/GPa). Admittance measurements were made to 4 GPa and C-V and C-f data interpreted in terms of standard models to yield the density of interface states. It was found that within experimental error this density did not change with pressure.

However, the technique is sensitive to the thickness of the SiO_2 layer and the data were consistent with a densification of the SiO_2 layer that persisted after depressurization, but increased towards its original value over a period of several days. As mentioned in Section 1 these are the first capacitance data obtained in the DAC, and the technique shows promise of yielding valuable information on interface states if it is developed to allow deep-level transient spectroscopy measurements to be made. The results of the work are summarized in the M.S. thesis of Todd Crumbaker (1987) and journal articles are in preparation for J. Appl. Phys and Rev. Sci. Instrum. (Crumbaker, Spain and Sites, 1987a and b).

2.5 Photoluminescence Measurements on InP

The crossover of the direct and indirect conduction bands (Γ_c -X band crossover) in InP has not been observed directly from photoluminescence measurements at room temperature. It was conjectured that PL measurements at lower temperature would allow the photons emitted from the X-levels to the valence band maximum (Γ_v) to be detected, and an experiment was carried out at 20 K to 11 GPa (Menoni, Hochheimer and Spain, 1986). Unfortunately these $X\text{-}\Gamma_c$ emissions were still too weak to detect, but an exponential drop in the direct transition ($\Gamma_c\text{-}\Gamma_v$) photon intensity was observed above about 6 GPa. It was determined that this was not due to a phase transition, and the data were interpreted on the basis of a model in which the $\Gamma_c\text{-}\Gamma_v$ transitions are quenched by the lowering of the occupancy of the Γ_c -levels by the Γ_c -X crossover. A crossover pressure of 7.0 ± 0.5 GPa was deduced from these measurements. This analysis, together with a discussion of the linearity of the PL energies with lattice spacing are discussed in the Ph.D. thesis of Carmen Menoni (1987) and a journal article is to be submitted to Phys. Rev. (Menoni and Spain, 1987b).

2.6 X-ray Diffraction of InP at High Pressure

It was important to characterize the variation of the lattice spacing of InP with pressure in order to allow experimental data to be compared to models of optical and electronic processes. Also, the transition to the metallic phase was characterized accurately to ensure that the decrease in PL intensity discussed above was not related to it. X-ray diffraction measurements were carried out to 20 GPa in the DAC. The equation of state of the zinc-blend phase was established for the first time, the metallic transition to the β -tin structure characterized, and a further transition to the rock-salt structure discovered. This work is published in Menoni and Spain, 1987a.

2.7 Metastable Phases of Si, GaAs, InP

It has been known since 1963 that Si and Ge can occur in metastable phases after decompression from their metallic phases. In our studies of Si in the DAC it was discovered that several different phases exist, depending on the manner in which the samples were decompressed. However, we were unable to produce Si in the ST-12 structure, which may have a direct band-gap of about 2 eV, as suggested to us by Dr. Richard Martin of Xerox Research Labs. Such a semiconductor would be of technological interest. This work is published in Zhao, Buehler, Sites and Spain, 1986.

Dr. B. Weinstein of Xerox Research Labs requested that we investigate the possibility that GaAs also exists in a metastable phase, since he observed that GaAs/AlGaAs MQWs became opaque after pressurization above 12 GPa. Metastable phases of GaAs and InP were then identified by us after quenching them from their metallic phases. This work is to be submitted to the J. Appl. Phys. (Chen, Patel, Sites and Spain, 1987).

2.8 Photoluminescence Measurements on a GaAs/AlGaAs MQW

Photoluminescence measurements were carried out on a MQW p-i-n diode supplied by Dr. Gary Vezzoli of ARDEC, New Jersey. PL signals could be detected at room temperature from a surface (capping) layer of AlGaAs, and two different regions of the MQW of different well thicknesses. Results obtained to 4 GPa in the DAC were interpreted in terms of a model of the energy levels and their shifts with pressure. This work is reported in Prins, Lambkin, Dunstan and Spain, 1987a. Further work has been carried out with PL and electro-photoluminescence measurements at low temperature in the DAC. This work will be submitted to the J. Phys. (Prins et al., 1987b).

2.9 Reviews of Semiconductor Physics at High Pressure

A review of techniques for semiconductor research at high pressure was given at the NATO Conference on Optical Properties of Narrow-Gap, Low-Dimensional Structures, St. Andrews, Scotland, July, 1986. A journal article on this subject was prepared (Spain, 1987a). A general article on the use of DACs for semiconductor research has been submitted to Contemp. Phys. (Spain, 1987b).

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- (8) D. Patel, J. R. Sites, and I. L. Spain (1987b). "Pressure Dependence of Electron Transport in InP," Appl. Phys. Lett. 50, 1829-1831.
- (9) A. D. Prins, J. D. Lambkin, D. J. Dunstan and I. L. Spain (1987a). "The Effect of Pressure on the Photoluminescence Spectrum of a Multiple Quantum Well p-i-n-Diode," accepted by Opt. Engr.
- (10) I. L. Spain (1987b). "Semiconductors at High Pressure--New Physics with the Diamond Anvil Cell," accepted by Contemp. Phys.

In Preparation

- (11) J. H. Chen, D. Patel, C. S. Menoni, J. R. Sites and I. L. Spain (1987). "Metastable Phases of GaAs and InP," to be submitted to J. Appl. Phys.

- (12) T. E. Crumbaker, J. R. Sites and I. L. Spain (1987a). "Admittance Measurements on a Si/SiO₂/Al MOS Capacitance to 5 GPa," to be submitted to J. Appl. Phys.
- (13) T. E. Crumbaker, J. R. Sites and I. L. Spain (1987b). "Techniques for Admittance Measurements in the Diamond Anvil Cell--Application to a MOS Capacitor," to be submitted to Rev. Sci. Instrum.
- (14) D. J. Dunstan and I. L. Spain (1987). "Small Diamond Anvil Cells for High Pressure Measurements at Low Temperature," to be submitted to Rev. Sci. Instrum.
- (15) C. S. Menoni and I. L. Spain (1987b). "Dielectric Theory and the Energy Gap Variation of II-V Semiconductors, and the T_c-X band Crossover in InP," to be submitted to Phys. Rev.
- (16) A. D. Prins, J. D. Lambkin, D. J. Dunstan and I. L. Spain (1987b). "Photoluminescence and Electro-Photoluminescence Measurements on a Multiple-Quantum-Well p-i-n Diode," to be submitted to J. Phys. C (Solid State Phys.).

4. PARTICIPATING PERSONNEL

Ian L. Spain	Professor
James R. Sites	Professor
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You-Xiang Zhao	Research Associate
Carmen Menoni	Graduate Student
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Todd Crumbaker	Graduate Student
Fred Bushler	Graduate Student
Paul Erdman	Graduate Student
Jianhui Chen	Graduate Student
Ping Han	Graduate Student
Charles Bowers	Undergraduate Student

Thesis Degrees Completed:

Carmen Menoni, Ph.D., 1987: "The Influence of Pressure on Ge and InP."

Todd A. Crumbaker, M.S., 1987: "Admittance Measurements on a Silicon Metal-Oxide-Semiconductor Capacitor Under Pressure."

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